Towards a Cost-Effective Operation of Low-Inertia Power Systems

A thesis submitted to Imperial College London for the degree of Doctor of Philosophy

Abstract

Modern power systems throughout the world, particularly in islands such as Great Britain, face a major problem: the significantly reduced level of system inertia due to integration of renewable energy sources. Inertia, which refers to the physical inertia of the rotating masses in thermal generators, acts as a buffer of kinetic energy, which helps prevent blackouts in the event of an unexpected generator outage. Given that most renewables such as wind and solar are decoupled from the power grid through power electronics converters, they do not naturally contribute to system inertia, therefore reducing this valuable energy buffer. In order to avoid blackouts in low-carbon systems, a higher amount of alternative ancillary services such as frequency response becomes necessary.

This thesis aims to facilitate a cost-effective integration of renewable energies, by developing mathematical models to operate electricity grids and markets efficiently. The main focus is the low-inertia challenge in modern electricity grids, which increases the risk of frequency instability: in plain words, we have studied how to optimally buy "insurance" against power blackouts. This is done by deducing novel frequency-stability conditions and implementing them as constraints into optimisation routines (such as a wholesale electricity market clearing), all while achieving computational efficiency. The key challenge lies in incorporating the differential-equation-driven frequency dynamics into an algebraic-equation-constrained optimisation problem. However, in the present thesis we overcome this challenge and propose a mathematical framework that allows to simultaneously optimise the provision of energy and frequency ancillary services.

The developed frequency-secured optimisation framework has been applied to several relevant case studies, which allow to inform sensible designs for ancillary-services markets and planning decisions that would lead to an optimal operation of a low-carbon power system. We demonstrate that the proposed operation strategies would achieve significant economic savings and reduction in carbon emissions. An optimal procurement of these ancillary services is of uttermost practical relevance in modern power grids, as highlighted by recent events such as the Great Britain blackout of August 9th 2019.

1. Motivation and background

The integration of renewable energy sources in a power system involves significant challenges. A traditional power system is dominated by relatively flexible and controllable generation plants, that follow a fluctuating but low-uncertain demand. However, the future low-carbon Great Britain electricity system will be characterised by a generation mix including significant amounts of difficult to predict, intermittent renewables, mainly wind and solar, in combination with a highly inflexible nuclear fleet. Therefore, a fundamental review of the current methodologies for the system's control, operation and planning is needed. This thesis addresses the operational aspects of low-carbon grids from the economic and engineering perspectives.

One of the major problems in the operation of a power system with high renewable penetration is a significant deterioration in electric frequency performance. This presents a threat to security of supply, which has been a crucial issue since the use of electricity became widespread: our society is absolutely dependent on electricity, and therefore electric utilities incur enormous economic penalties in the event of a blackout. In order to guarantee electricity supply, frequency stability must be assured, which means that the system's electric frequency must be contained within a narrow band around the nominal value of 50Hz. Outside this secure range generating units could be damaged, so they would be disconnected from the grid by the action of protection devices. This could in turn cause a cascading failure and the system could then potentially reach a blackout state.

Frequency deviations from steady state are due to a generation-demand imbalance. The electric frequency in the grid is determined by the rotating speed of thermal generators, which spontaneously slow down when demand is higher than generation, as they release the kinetic energy in their rotating masses in order to restore the power equilibrium. Therefore, in the event of an unplanned generation outage in the system, frequency would drop rapidly and significantly. The rate at which the frequency drops is inversely proportional to the level of inertia in the power grid. The aforementioned deterioration of frequency performance in low-carbon grids is due to a greatly reduced level of inertia in the system, as most renewables such as wind and solar are decoupled from the grid through power electronics converters and therefore do not naturally contribute to system inertia.

In order to assure a secure operation of the grid, system operators procure certain frequency services that would only come into play in the event of a frequency drop. Frequency services are any type of ancillary service that helps contain a frequency decline, that is, that helps restore a power equilibrium after a generation/demand outage. Frequency services are: inertia, frequency response (a power injection from some devices following the outage), load damping (provided by frequency-responsive loads that reduce their consumption after a frequency drop) and the size of the largest possible loss of generation (since the grid must withstand any single failure of a device, operators plan for the worst possible case).

While system inertia and frequency response were services widely available in grids dominated by thermal generation (e.g. gas, coal) as by-products of energy production, the increasing scarcity of these services in low-carbon system increments the costs associated to their provision. The cost of operating a traditional power system, was mainly driven by the cost of burning fuel for energy production, but modern renewables-dominated grids show a different behaviour: the overall cost of operating the grid is reduced, since there is no fuel cost associated with renewables, but the fraction of total cost due to providing frequency services has greatly increased, and could reach more than 30% of total costs in a carbon-free electricity system. This cost increase could be a barrier to further increasing the share of renewables if efficient methods for procuring frequency services are not available.

In this context, several works have studied optimal strategies to procure inertia and frequency response. However, since frequency-constrained optimisation is a relatively new area of research, several questions are still open, notably: 1) how to obtain stability conditions while considering multi-speed frequency response; 2) how to optimally schedule the size of the largest loss; and 3) how to model regional variations in post-fault frequency within a power system. All these questions are addressed in the present thesis.

2. Problem statement and research approach

The main goal of this PhD thesis is to facilitate the integration of renewables in a cost-effective manner by developing efficient ways to procure energy and frequency ancillary services. The simultaneous optimisation of energy and frequency services can be achieved by appropriately constraining a market clearing to guarantee frequency stability. The key challenge for obtaining frequency constraints lies on the mathematical complexity of incorporating the differential-equation-driven frequency evolution into the algebraic-equation-constrained optimisation problem. This challenge of mapping the differential equations that describe frequency dynamics into algebraic constraints applicable to a market algorithm comes from the distinct time-scales of both problems: while the market clearing is typically performed every hour, and certainly not more frequently than every few minutes by any system operator, the period of interest for frequency dynamics ranges from sub-seconds to tens of seconds.

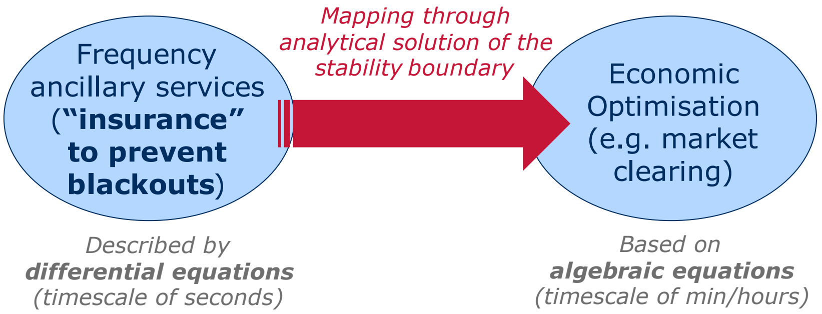

Figure 1: The main research question tackled in this thesis is *How to optimally procure the ancillary services needed because of low inertia?* The challenge in answering this question comes from mapping the sub-second timescale of ancillary services into the hourly timescale of electricity markets.

With the emergence of new technologies in power grids, new possibilities arise for the delivery of frequency response. Some devices such as grid-scale battery storage have much faster dynamics than thermal generators, and therefore can deliver frequency response in a significantly shorter time. Therefore, **the first research question tackled in this thesis** was *how to optimise the frequency-response dynamics from fast devices such as battery storage*. These fast dynamics had already been identified by some system operators as a valuable resource to cope with the low-inertia problem, like National Grid, who introduced in 2017 the Enhanced Frequency Response (EFR) service. In the past, Primary Frequency Response (PFR) was the only service considered to contain a frequency decline, for which response must be delivered within ten seconds after a generation-demand imbalance, while EFR must be delivered in just one second. However, no tool was available to co-optimise the provision of these two services.

A graphical description of the frequency-response services defined in Great Britain (GB) at the time of writing this thesis is included in Figure 2, along with an illustration of post-fault frequency limits.

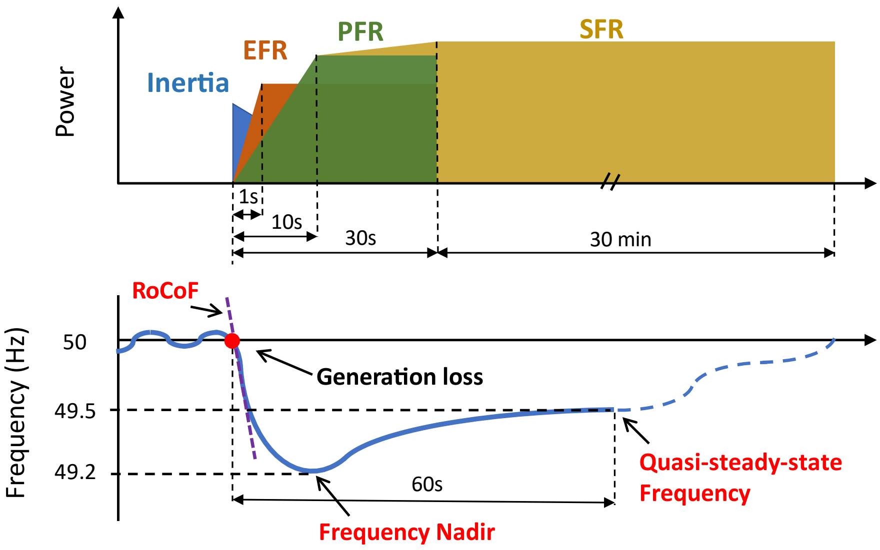

Figure 2: Post-fault frequency evolution and the limits that must be respected in Great Britain, along with the power contribution from the services that contain the frequency drop: inertia, Enhanced Frequency Response (EFR), Primary Frequency Response (PFR) and Secondary Frequency Response (SFR).

The second research question addressed in this work was *how to optimise the provision of frequency-response dynamics from any generic provider*, in order to extract the full value of flexibility available in a power system: instead of forcing devices to participate in either the EFR or the PFR services defined by National Grid, such a tool would allow a system operator to co-optimise the frequency response from devices that might not be able to comply with the one-second dynamics established for EFR but are faster than the ten-second definition for PFR.

Finally, **the last research question addressed** was *how to take into account different regional variations in electric frequency within the power system*. Although frequency has traditionally assumed to be roughly equal in all of the grid's buses, non-uniform distributions of inertia in some systems (driven by the typically remote location of some renewables such as wind), make this assumption less accurate. Ignoring this effect would compromise the stability of the grid.

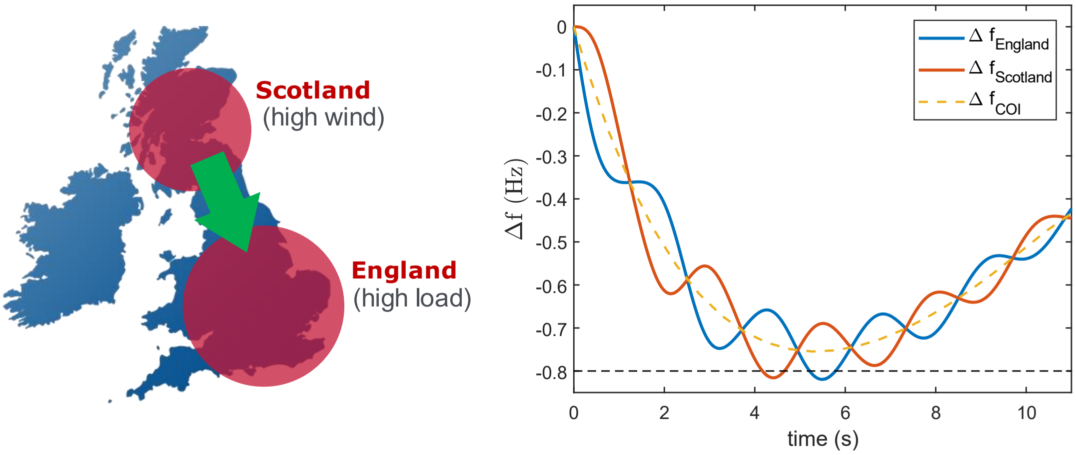

Figure 3: Inter-area frequency oscillations around the Centre of Inertia (COI) that appear when inertia is not evenly distributed in the grid (e.g. high wind capacity in Scotland but most of the electric loads located in England). This thesis is the first work to deduce stability conditions for these types of systems, demonstrating that ignoring these inter-area oscillations would compromise stability.

The methodology chosen to tackle all these research questions was to obtain analytical, closed-form solutions for the frequency-stability boundary. The choice for deducing stability conditions by using analytical methods was driven by the rigorous mathematical descriptions of the frequency-stability boundary that these methods provide, as opposed to the heuristics needed for some methods proposed in the literature which are based on solving comprehensive dynamic simulations of the system. Once the frequency-stability constraints are deduced, they can be implemented in optimisation problems to understand the implications of operating a low-inertia electricity grid.

3. Original contributions

The main contributions of this thesis are four-fold:

- To **develop novel mathematical models that allow to optimise new frequency services** that have been proposed by some system operators like National Grid (EFR, reduced largest loss) or have been envisioned for the future (multi-speed frequency response, market for inertia).
- To **develop a marginal-pricing scheme** for frequency ancillary services that would **put in place the right incentives for providers to improve their characteristics**, allowing for the first time to appropriately value inertia and multi-speed frequency response.
- To **ensure the computational efficiency of the deduced frequency constraints**, which are implemented in the burdensome Stochastic Unit Commitment (SUC) problem. By running SUC simulations we are able to analyse the value of new technologies, such as EFR from battery storage or synthetic inertia from wind turbines.
- To **deduce, for the first time, conditions for regional frequency stability in a power grid**. As the uniform frequency model is becoming less accurate due to non-uniform distributions of inertia, there is a need to go beyond this model for modelling post-fault frequency evolution. This thesis does so and obtains constraints that guarantee stability in a multi-region system.

An example of the advantages of the novel strategies proposed in this thesis is given in Figure 4: part-loading large nuclear units can reduce overall carbon emissions. This might seem contradictory, since nuclear plants are carbon free, but part-loading them implies that less thermal generators (e.g. gas, coal) are needed to run simply for stability purposes. Since large nuclear plants set the amount of ancillary services needed (as they are the largest units in the system, and there must be sufficient ancillary services to cover for the loss of any unit in the system), part-loading these units during periods of high renewable output achieves both economic savings and a reduction in carbon emissions.

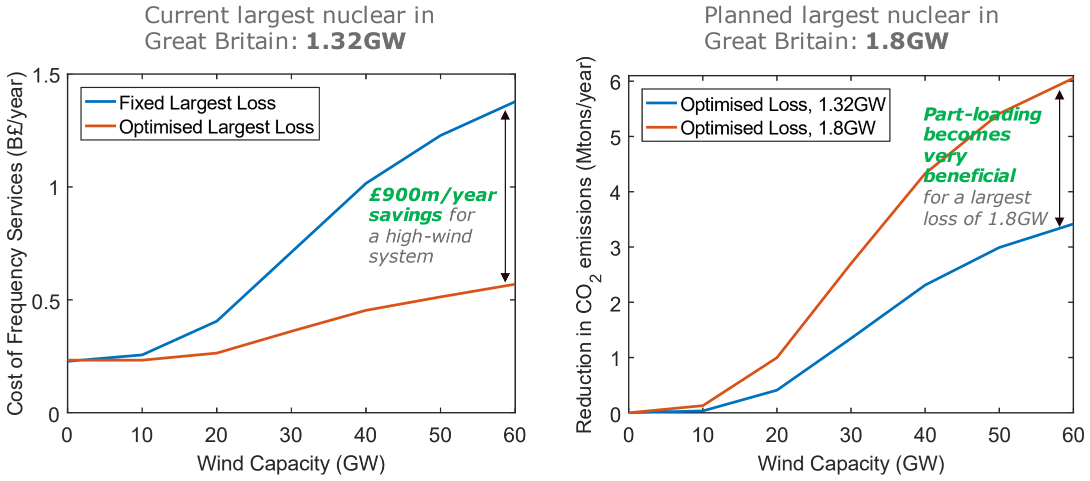

Figure 4: Benefits of optimally part-loading large nuclear units to reduce the need for ancillary services during periods of high renewable generation.